APPLICATION OF STATISTICALLY CAPABLE SHOT PEENING TO AUTOMOTIVE COMPONENT DESIGN

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ABSTRACT

Today's world automotive business climate is demanding more cost effective, higher strength/weight designs than ever before. Engineering coverage factors are shrinking and, at the same time, designs are becoming more robust. Consequently, manufacturing processes without a quantified benefit/cost ratio are being discarded. Those processes that are utilized are required to statistically demonstrate acceptable product performance.

This paper will examine the application of the shot peen process to automotive components where the process design intent is dependant upon meeting a minimum fatigue strength objective. Specific automotive component application testwork, process engineering, and Advanced Quality Planning necessary to produce the statistical control limits resulting in acceptable product performance will be discussed as well as production monitoring requirements for statistical capability. The benefit/cost ratio of such a process will then be analyzed in light of conventional controlled shot peening and other strength enhancement processes applied to the same component.

KEYWORDS

coverage factors, Advanced Quality Planning, statistical capability, benefit/cost ratio, parameter, variable, "sweet zone", strength/weight, time-to-manufacture.

INTRODUCTION

The following definitions are important to understanding this paper:

Parameter:	Any of a set of physical properties whose values determine the characteristics or behavior of the process. i.e, shot velocity, shot size, shot impact angle, etc.
Variables:	A machine or media specific quantity that may assume any one of a set of values, thus influencing a parameter value. i.e, air pressure, shot breakdown rate, shot flow rate, etc.

The potential for fatigue strength increases of 25% - 50% due to shot peening has been well documented (1) (2) (3) (4) (5) (6). It has also been established that there is a strong correlation between process parameter values and the magnitude of the fatigue strength increase induced by shot peening. Numerous publications support the fact that unique optimum peening process parameter values or ranges exist for specific workpiece characteristics (6) (7) (8). As far back as 1943, John Almen identified the concept of a peening intensity "sweet zone" (9).

If fatigue strength increases of 25% - 50% were obtainable from a particular technology, it seems logical that such benefits would be systematically included in product design unless process reliability and/or cost were a barrier. Numerous cases of high fatigue strength benefit produced in testwork followed by excessive fatigue strength variability once in production, have characterized the history of the shot peen process. Consequently, shot peening has become a process of last resort, rather than a process of choice.

Assuming relatively inclusion free material, when the fatigue strength scatter of the peened population is significantly broader than the nonpeened, the increase in variability can only be attributed to shot peening variability. This is especially significant, considering the fact that fatigue strength scatter of the shot peened population should be less than the nonpeened. This is due to shot peening's mitigating influence on the contribution to fatigue strength variability of pre-peen manufacturing processes such as machining and heat treating, which can respectively produce surface residual tensile stress and decarburization (10) (11) (12). Under these circumstances, the increase in fatigue strength variability can only be attributed to critical peening process parameters fluctuating in and out of their "sweet zones" or optimum tolerances.

To further complicate matters, conventional controlled shot peening has utilized the almen strip measurement system and visual coverage as the primary process monitoring tools. The reasons this system is inadequate for producing acceptable fatigue strength variability have been well documented:

1. Almen intensity provides an indication of the aggregate amount of energy transfer to the workpiece without defining the individual contributing process parameters and variables (13) (14).
2. The effect of the cumulative tolerances within the almen strip system itself will, in most cases, result in undetected process variation that is too excessive for acceptably reliable fatigue performance (15) (16) (17).

3. Visual coverage is a qualitative attempt to relate almen saturation to workpiece saturation (13). They often do not occur simultaneously due to differences in surface hardness and metallurgy. In addition to the obvious weakness of inspector judgement, tracer dyes and coatings notwithstanding, it is impossible for a human to visually discern coverage levels above 100% or between primary or secondary impact impingement (13). Additionally, in many cases the optimum workpiece saturation level is above 100% coverage (8). (See (13) for monitoring 100% + coverage levels).

Finally, this almen strip/visual coverage measurement system is the foundation upon which all industry and military shot peening specifications rest. No matter how well one complies with these specifications, if they are the sole governing criteria, it has been statistically demonstrated that unacceptable fatigue strength variability is a highly likely result. The specifications can be no more statistically reliable than the process measurement system used (16).

For the reasons described above, the conventional approach of engineering a shot peen process based solely upon almen intensity and coverage values (whether these values are derived from cursory testwork or from published shot peen specification recommendations) is highly unlikely to produce statistically reliable fatigue strength gains, and therefore, justifiable benefit/cost ratio results.

In the authors opinion, obtaining statistical reliability begins by relating specific levels of critical shot peen process parameters directly to the fatigue performance of the workpiece. (See (6) (16) (18) (19) and (20) for a more in-depth treatment of the type of work involved). The data derived from this testwork provides the peening process parameter optimum values and the process variable tolerance values for engineering a statistically reliable shot peen process. Without this data, the likelihood that a specific shot peen process will produce unacceptable variability (when process variable tolerances are too broad), suboptimum fatigue strength (when optimum process parameter values are unidentified), or unnecessary cost (when variable tolerances are maintained to tighter than necessary values) is very high (8) (16).

Engineering a shot peen process by statistically relating specific levels of peening process parameters and variables to workpiece fatigue strength performance is, in the authors opinion, the way to reliably reproduce, in high production volumes, the high level of fatigue strength benefit the shot peen process has historically been capable of developing in the laboratory. The following will briefly summarize this method. This will be followed by an example of how the Ford

Motor Company used this technique and the benefit/cost ratio that resulted.

DISCUSSION

The engineering method

Typically a shot peen production process is engineered in the following manner:

1. The component is shot peened to an almen intensity and coverage value chosen from past internal specifications or from published industry or military specification / recommendations.
2. If the component passes the fatigue test, the production process is defined using almen intensity value, coverage and shot size. Also, in some cases compliance to a published industry or military specification is required.
3. If the component fails the fatigue tests, another almen intensity value is tried or shot peening is abandoned for another solution.

Because of the reasons stated in the introduction, sole reliance upon the almen strip process monitoring system and almen strip based specifications is an unreliable approach to either determine if shot peening can solve a particular fatigue problem, or to implement a shot peening solution into production. To do so will, in most cases, result in undetected process variation that is excessive. Without statistically defining each parameter optimum value and acceptable variable tolerance based upon the effect on fatigue strength magnitude and variability, one has no established reference points in the search for optimum benefit/cost ratio during testwork, and similarly no assurance the reproduction of that sweet zone is occurring in production (16).

Table 1 lists the peening process parameters, and Table 2 lists the peening process variables.

Table 1

Process parameters critical to fatigue strength			
1.	Shot velocity	5.	Shot impact angle
2.	Shot diameter	6.	Nozzle to workpiece position relationship
3.	Shot hardness	7.	Workpiece saturation
4.	Shot type/density		

Table 3 provides an outline of the steps to statistically engineer a fatigue strength based shot peen process. "The defining element of this approach is that the ultimate goal

Table 2

Process variables critical to statistical reliability

1. Shot size distribution
2. Shot shape distribution
3. Shot flow rate
4. Air pressure
5. Shot blast pattern
6. Exposure time
7. Workpiece motion

shouldn't be to meet the requirements of any particular specification or even any particular shot peening intensity. Rather it should be to achieve, within acceptable statistical reliability, certain desired levels of process induced benefit on a statistically acceptable percentage of production workpieces" (16). The amount of testwork required to accomplish this is not inexpensive or quick. However, once a database is established, the number of test iterations necessary to establish process parameters is reduced, shortening the time to engineer the process.

Table 3

Steps for statistically engineering a fatigue strength based shot peen process.

1. Analysis of workpiece failure mode via SEM, FEA, and/or baseline fatigue testing.
2. Define optimum peening process parameter test matrix based upon above analysis and data base using statistical design of experiments methodology.
3. Determine optimum value for each critical process parameter with the corresponding fatigue strength distribution utilizing testwork peening machinery whose control capability meets or exceeds Table 4.
4. Define minimum fatigue strength requirements and the statistical indices necessary to assure compliance.
5. Determine critical process variable tolerances based upon their cumulative effect on fatigue strength requirements.
6. Define process control limits based upon item 5.
7. Obtain high production peening equipment with statistical capability within the defined process control limits.
8. Use statistics to monitor process variable trends in production.
9. Statistically sample workpiece fatigue performance.

Properly performed, the resultant benefit/cost ratio of a production shot peen process so defined can be unprecendentedly high. Once such a capability is obtained, the strategic advantage afforded an automobile manufacturer in terms of design strength/weight, manufacturing costs, product performance, and time-to-manufacture, are just as significant.

The following is a typical example of applying these engineering principles.

An application

In 1986, Ford Motor Company introduced the Ford Taurus and Mercury Sable four door sedans. These cars were equipped with the newly designed AXOD (Automatic Transaxle with Overdrive) transmission, applied to a 3.0 liter (3.0L), V-6 engine capable of 135 horsepower. In 1989, this transmission was scheduled to be applied to the new Lincoln Continental, equipped with a 3.8 liter (3.8L), V-6 engine capable of 140 horsepower. Finally, in 1992, this same transmission was called upon to handle the 220 horsepower, 3.2 liter (3.2L) SHO (super high output), V-6 four valve engine application.

A consideration for the first upgrade of the AXOD transmission for the Lincoln Continental, and subsequently for the second upgrade for the Taurus SHO, was the final drive planetary pinion gearset. The purpose for the gearset is to multiply the torque between the primary geartrain and the vehicle axle.

The workpiece was a helical pinion machined from 5130 steel and carburized to a case hardness of 58 - 62 Rc. The failure mode, as defined by Finite Element Analysis (FEA), was gear tooth bending fatigue. This was confirmed with dynamometer fatigue testing and Scanning Electron Microscopy (SEM) failure analysis.

The requirement for validating the transmission for the Lincoln Continental (3.8L) application was a 9.25 hour B-10 life, at a predetermined dynamometer low gear torque output. (Note, due to the proprietary nature of this testwork, the actual torque requirements will not be disclosed).

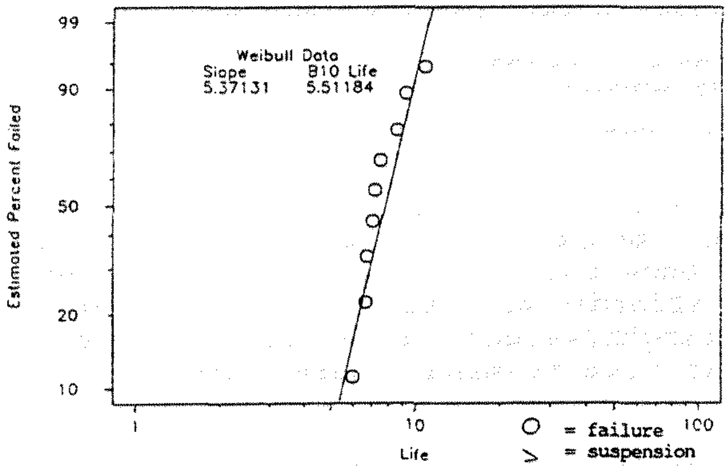

Figure 1. Weibull probability plot of gear life at 3.8L loads without shotpeen.

The transmission as applied to the 3.8L engine had a B-10 life of approximately 5.5 hours as shown in Fig. 1.

A peening process parameter test matrix was developed with the objective of generating a 68% increase in B-10 life. Referring to Table 1, the process parameters initially studied were shot velocity, shot diameter, and shot impact angle. The shot used was cast steel with a density of 7 gms./ml. and hardness of 55 - 60 Rc. The size distribution was maintained to the range of 0.0139 inch diameter to 0.0165 inch diameter. All variables listed in Table 2 were maintained per Table 4.

The optimum process parameter values were determined from fatigue life data gathered from three months of dynamometer testwork. Fig. 2, which illustrates the final results of this testwork, demonstrates a 165% increase in B-10 life.

Table 4

Typical example of precision peening equipment process control capability.

Process Parameter	Tolerance	*	#
1. Air pressure	+/- 0.75 psi	x	x
2. Shot size distribution	95% between 0.0138" dia. and 0.0165" dia.	x	
3. Shot shape	< 5% broken		x
4. Shot impact angle	+/- 2 degrees	x	x
5. Shot flow rate	+/- 2 oz./sec.	x	x
6. Nozzle to workpiece position relationship:			
via workpiece fixture position repeatability	+/- 0.001"	x	x
via workpiece height fiber optic eye	- 0 + 0.062"		x
via workpiece rpm sensor	+/- 2%	x	x
7. Exposure time:			
minimum via timer	+/- 0.25 sec.	x	x
maximum via computer	+/- 0.25 sec.	x	x

* = maintained by the machine # = monitored electronically

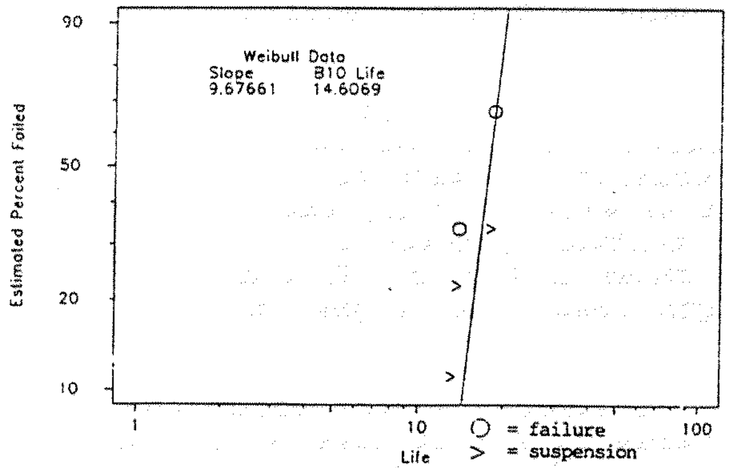

Figure 2. Weibull probability plot of gear life potential at 3.8L loads using shotpeen.

This testwork showed the potential fatigue strength improvement obtainable through optimized shot peening and would become valuable for the next upgrade of this transmission.

The next phase of testwork, defining minimum fatigue strength requirements and the corresponding process variable tolerances necessary to assure compliance (see Table 3 step 4 & 5) required another four months of testwork and produced the results shown in Fig. 3. This data represents the lowest cost process necessary to statistically assure compliance with the B-10 life requirement of 9.25 hours at the validation torque requirement.

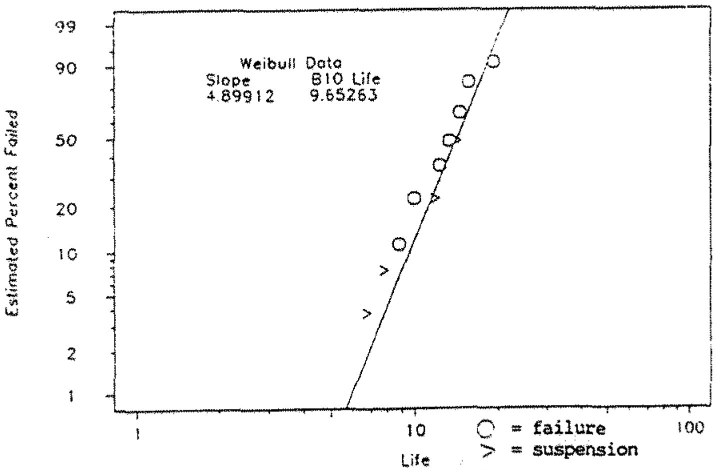

Figure 3. Weibull probability plot of gear life at 3.8L loads with lowest cost shotpeen.

From this data and the background data, the process control limits were defined and the corresponding high production peening equipment process control requirements were determined (see Table 3 steps 6 & 7).

Since implementing into production in September 1988, the production process has continued to produce final drive planetary pinions that meet the requirements for statistically acceptable product performance (Table 3 steps 8 & 9). See (21) & (22) for the type of statistical measures the authors suggest employing to monitor a shot peen process.

The testwork for upgrading the AXOD transmission for the Taurus SHO (3.2L, 4 valve) application was performed in similar fashion. The dynamometer validation torque requirement was increased 12.5% over the 3.8L validation requirement with the same B-10 life requirement of 9.25 hours.

Testwork indicated that the current production shot peening process produced inadequate fatigue strength at the higher torque levels. The decision was made to upgrade the gear steel from 5130 to 8620 as well as to implement the previous shot peen optimization testwork process utilized during the 3.8L upgrade testwork, shown in Fig. 2. This data indicated greater fatigue strength results at higher peening energy transfer levels.

Fig. 4 illustrates the testwork results after completing steps 1 through 3 in Table 3. A B-10 life of 11 hours was obtained at the higher torque levels. Once again, completing steps 4 and 5 in Table 3 resulted in reducing shot peen process costs with a lowering of the energy transfer to a level between the 3.8L production peen process and the optimized level shown in Fig. 4.

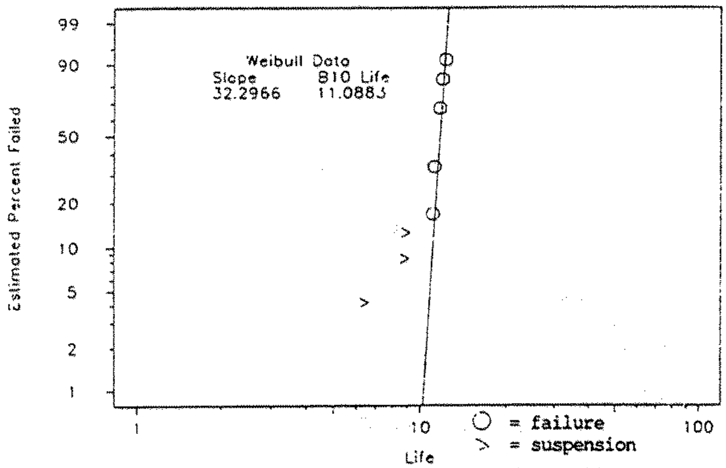

Figure 4. Weibull probability plot of gear life potential at 3.2L SHO loads using shotpeen.

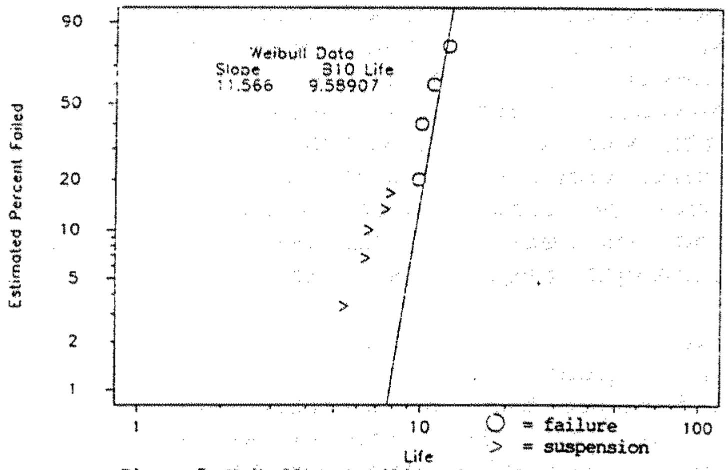

Figure 5. Weibull probability plot of gear life at 3.2L SHO loads with lowest cost shotpeen.

The resultant data and B-10 life of 9.6 hours is shown in Fig. 5.

Benefit/cost comparison

The following will analyze the justification of such an expensive endeavor based upon comparing the resultant benefit/cost ratio (B/C) to the other options available.

For discussion purposes, the authors define B/C as the percentage increase in horsepower rating divided by the cost of obtaining the increase. The baseline for comparison is a 63% increase in horsepower application at a cost of less than $1.00 per transmission. This produces a B/C of greater than 63.

Other options available for increasing horsepower rating include designing a larger transmission and using a higher strength steel. The cost associated with designing, validating, and tooling for production of a new gearset is conservatively estimated to be in the multiple millions of dollars. The resultant B/C is less than 0.0001. Not accounted for in this figure is the corresponding performance and fuel economy penalties resulting from the weight increase associated with a larger transmission, as well as the time-to-manufacture penalty measured in years.

Upgrading to higher fatigue strength steels usually results in higher machining, heat treat, and raw material costs.

Only a limited amount of fatigue strength improvement can be obtained, such as the change from 5130 to 8620 or 4615M, without the cost increases reaching significant proportions. Changing to either of these materials still requires the application of shot peening to produce the required fatigue strength.

To obtain a comparable fatigue strength increase without shot peening would require materials in the class of 9310 or Aermet 100, both used in aerospace applications. These materials, besides being more expensive, must be subjected to additional heat treatments to achieve a machineable structure, plus additional operations to eliminate austenitic microstructure. If we assume a $2.00 - $3.00 cost penalty for using this material, the resultant B/C ratio is 25.2. Not included in this figure is the time-to-manufacture penalty of 2 - 3 years for validation and tooling.

Another option to consider is conventional controlled shot peening. It has been demonstrated, and now is commonly accepted, that statistical process control increases quality while reducing cost (23). Therefore although unquantified in this example, conventional controlled shot peening, as defined in this paper, will lack the level of fatigue strength benefit obtainable with statistically capable shot peening. If it were possible to obtain a comparable benefit, the costs associated with such a hypothetical scenerio would be higher for conventional controlled shot peening than for statistically capable shot peening. This is due to the fact that the statistical indices necessary to assure compliance to a minimum fatigue strength requirement are unknown.

The time-to-manufacture required for engineering a statistically capable shot peen process ranges from 3 to 14 months, depending upon fatigue test scheduling and existing shot peen capacity availability. This characteristic of the shot peen process becomes a benefit when comparing to time-to-manufacture for transmission redesign and for material upgrades.

Summary

Table 5 provides a comparison of the cost effectiveness associated with alternatives for increasing the strength of the AXOD final drive planetary gearset. The requirement was a 63% increase in horsepower capacity.

Statistically capable shot peening, as described by the authors, has the highest benefit/cost ratio (B/C) and the shortest time-to-manufacture of all the strengthening options available to Ford. Conventional controlled shot peening is the worst choice due to its lack of statistical capability.

Table 5

Cost effectiveness comparisons of options for increasing AXOD transmission strength.

	Statistically Capable Shot Peening	Redesign	Material Upgrade	Conventional Shot Peening
B/C	63	0.0001	25.2	lower
Time-to-manufacture	3 - 4 months	3 - 5 years	2 - 3 years	1- 12 months

A statistically capable shot peen process is based upon statistically relating critical peening process parameters to actual workpiece strength. A conventional controlled shot peen process is based upon the statistically incapable almen strip measurement system. A statistically capable shot peen process is one of the most cost effective technologies for increasing automotive transmission capacity.

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